Review

Pacing profiles and tactical behaviors of elite runners

Running head: *Pacing in elite distance runners*

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Highlights:

- Elite athletes' pacing behaviors differ depending on race distance and whether races longer than 800 m are conducted during championships or "meets".
- Optimizing finishing position requires the adoption of a leading position with as much as a lap remaining in 1500 m and 5000 m championship races.
- Staying within a pack of runners who follow a realistic, non-excessive pace from the beginning of major championship long-distance races is also recommended to optimize performance (finishing time).

Abstract

The pacing behaviors used by elite athletes differ among individual sports, necessitating the study of sport-specific pacing profiles. Additionally, pacing behaviors adopted by elite runners differ depending on race distance. An "all-out" strategy, characterized by initial rapid

acceleration and reduction in speed in the later stages, is observed during 100 m and 200 m events; 400 m runners also display positive pacing patterns, which is characterized by a reduction in speed throughout the race. Similarly, 800 m runners typically adopt a positive pacing strategy during paced "meet" races. However, during championship races, depending on the tactical approaches used by dominant athletes, pacing can be either positive or negative (characterized by an increase in speed throughout). A U-shaped pacing strategy (characterized by a faster start and end than during the middle part of the race) is evident during world record performances at meet races in 1500 m, mile, 5000 m and 10,000 m events. Although a parabolic J-shaped pacing profile (in which the start is faster than the middle part of the race but is slower than the endspurt) can be observed during championship 1500 m races, a negative pacing strategy with microvariations of pace is adopted by 5000 m and 10,000 m runners in championship races. Major cross country and marathon championship races are characterized by a positive pacing strategy; whereas a U-shaped pacing strategy, which is the result of a fast endspurt, is adopted by 3000 m steeplechasers and half marathoners. In contrast, recent world record marathon performances have been characterized by even pacing, which emphasizes the differences between championship and meet races at distances longer than 800 m. Studies reviewed suggest further recommendations for athletes. 800 m runners should avoid running wide on the bends throughout the whole race. In turn, during major championship events, 1500 m, 5000 m, and 10,000 m runners should try to run close to the inside of the track as much as possible during the decisive stages of the race when the speed is high. Staying within the leading positions during the last lap is recommended to optimize finishing position during 1500 m and 5000 m major championship races. Athletes with more modest aims than winning a medal at major championships are advised to adopt a realistic pace during the initial stages of long-distance races and stay within a pack of runners. Coaches of elite athletes should take into account the observed difference in pacing profiles adopted in meet races *vs.* those used in championship races: fast times achieved during races with the help of one or more pacemakers are not necessarily replicated in winner-takes-all championship races, where pace varies substantially. Although existing studies examining pacing characteristics in elite runners through an observational approach provide highly ecologically valid performance data, they provide little information regarding the underpinning mechanisms that explain the behaviors shown. Therefore, further research is needed in order to make a meaningful impact on the discipline. Researchers should design and conduct interventions that enable athletes to carefully choose strategies that are not influenced by poor decisions made by other competitors, allowing these athletes to develop more optimal and successful behaviors.

Keywords: Athletics; Distance running; Pacing; Sprinting

1. Introduction

Pacing is the term used to describe the distribution of muscular work throughout an exercise bout. It is considered to be a fundamental requirement of successful endurance performance[1] and is reliant on continuous decision-making processes.[2] Strategic decisions regarding the overall approach to the event are made beforehand, whereas tactical decisions during the event respond to changes in physiological status and the behavior of rivals.[3] Pacing behaviors differ according to the mode of exercise, the event's duration, the knowledge and experience of the athlete and each opponent's physiological capacity.[4] Several pacing profiles were described in 2008 by Abbiss and Laursen,[5] including a negative profile (an increase in speed over the duration of the event), a positive profile (a decrease in speed over the duration of the event), an "all-out" profile (characterized by initial rapid acceleration and reduction in speed in the later stages), an even profile, a parabolic-shaped profile (including U-shaped, reverse J-shaped and J-shaped) and variable pacing.

These profiles were originally based on analyses that predominantly focused on swimming, cycling and rowing.[5] Not surprisingly, research on running was largely absent, given that sufficient high-resolution, official performance data from global championship track races (e.g., 800 m, 1500 m, 5000 m, and 10,000 m) were rarely available for analysis until 2008. Given the differences, such as aerodynamic drag, that exist between running and other individual sports like cycling and speed skating, there is a very strong rationale for updating the current understanding of pacing in running. Building on the excellent foundation laid by Abbiss and Laursen,[5] pacing profiles in running can now be established. The requirements for runners vary depending on the distance being run: middle-distance runners require a greater aerobic contribution than sprinters; long-distance runners face different challenges depending on whether they are competing on a track, on a road, or in cross country; and championship races emphasize winner-takes-all competitions in which the main goal is to either qualify to following rounds during heats and semifinals or to achieve either a finalist or a medalist position during the final race that contrast with regular meets, such as Diamond League events or big-city marathons, that employ pre-arranged pacemakers who set a specific pace from the beginning to help runners achieve the fastest possible finishing times. In addition, meet races do not involve preliminary rounds such as heats and semifinals and final races as championships do. These differences that exist among running events makes them an invaluable source for furthering our understanding of the pacing behaviors used by successful and unsuccessful athletes, by men and women and by runners within different competition formats. Such information can provide coaches and athletes with real-world insights into improving performance. Since the time that Abbiss and Laursen[5] published their early review of pacing research, an extensive body of new literature on pacing in running has been produced. In this paper, we examine the literature relating to elite running events. Furthermore, we explore differences between theoretically optimal pacing strategies and the behaviors that result from tactical decisions during championship racing, where the primary goal is to achieve a high finishing position rather than a fast time. In our review, the figures produced to illustrate pacing strategies are original and are based on the open-access data reported in the cited literature.

2. 100 m and 200 m

In short events, athletes adopt an “all-out” strategy,[5] as evidenced by the fact that 100 m and 200 m sprinters competing at the International Association of Athletics Federations (IAAF) World Championships achieved maximal speeds in the early stages followed by a progressive slowing until the finish line,[6–9] although the 200 m is usually run with a faster second half overall[10,11] (Fig. 1A–D). This pacing strategy is likely a product of the high energetic cost of acceleration. Achievement of a high initial speed in a sprint allows minimization of total energy cost, even if there is a progressive loss of speed.[5] It has been found that the acceleration phase required to achieve peak speed in the 100 m race covers 50%–60% of the total distance[6,7] and therefore it has been calculated that 20%–25% of the overall work performed is required to accelerate the body from the static starting position.[5] The all-out nature of these races suggests a minimal impact of strategic or tactical considerations on behaviors displayed in either championship or non-championship type races, which thus do not differ in speed profiles.

3. **400 m**

In contrast to the 100 m and 200 m events, observations made during 2 separate IAAF World Championships[6,12,13] suggest that truly maximal velocity is not achieved during 400 m races. Rather, the pace for 400 m is characterized by high, but not maximal, starting speeds and progressive deceleration, resulting in an overall positive profile[12,13] (Fig. 1E and F). As an illustration, Wayde Van Niekerk, the 2017 men's 400 m World Champion, recorded a split time of 10.69 s for the first 100 m in the final,[12] whereas in the same championships he recorded a split time of 10.15 s for the first 100 m during his silver medal run in the shorter 200 m final.[10]

In addition to the mechanical explanations for observed pacing behaviors in 400 m races, there are physiological mechanisms that partially account for them as well. Short and high-intensity exercise causes rapid depletion of intermuscular high-energy phosphates resulting in impairment of muscle contractility and force production. Nummela et al.[14] suggested that the gradual reduction in speed throughout most of the 400 m event was evidenced by a reduction in the ability of the muscles to generate force (i.e., peripheral physiological fatigue) despite a gradual increase in motor unit activation (measured using electromyography).

An important characteristic of the 100 m, 200 m, and 400 m sprint events is that athletes complete the entire distance in their own individually allocated lanes. This suggests that pacing behaviors during these sprint events are less strategic in nature than in longer events, where competitors are able to share the inside lane and can vary tactical behaviors related to minimization of distance covered[15] or energetic benefits gained by drafting behind other runners. However, due to the absence of these benefits in the sprints, pacing behavior in the shorter events should differ little between major championship races and meet races. Rather, any differences between these types of competitions could be related to the athlete's ability to recover from preliminary races, since major championships involve heats, semi-finals and a final within, at most, a 4-day period.[8,9] It is plausible that higher-performing athletes recover faster than athletes with less ability, whose performances are good enough to qualify for successive rounds during championships, but are at a higher speed relative to their season's best (SB) times than better athletes. In 2016, for example, 2 days before breaking the men's 400 m world and Olympic records in a time of 43.03 s, Wayde Van Niekerk (mentioned above) ran his 400 m heat in 45.26 s, more than 2 s slower than his record-setting time (data obtained from the open-access website www.worldathletics.org). Therefore, it is very likely that his 400 m heat did not require a considerable effort from him, especially when compared with the fatigue that his less-able rivals possibly felt.

4. 800 m

The 800 m is a middle-distance running event typically characterized by a positive pacing strategy similar to that displayed in 400 m running.[13,14] In contrast to the sprints, athletes in races of 800 m and longer are not confined to their own lanes (except for the first bend in the 800 m). This means that athletes must consider in their pacing strategies how running wide on the bends increases the total distance covered. Indeed, during the men's final at the Olympic Games in 2000, the eventual silver medalist had a faster mean speed than the winner, but lost because he ran a greater total distance through poor tactical and positional decision making.[15] Tucker et al.[16] analyzed lap times from 26 world record performances in the 800 m distance from 1912 to 1997 and found that the second lap of the race was consistently slower; indeed, on only two occasions was the second lap faster. Similarly, Sandford et al.[17] found that runners ran the first lap faster than the second lap in the 2012 Olympic 800 m final, in which the Kenyan runner David Rudisha established the current men's world record. de Koning et al.[18] also reported that positive pacing strategies were typically displayed in 800 m major championship races. These observations on pacing strategies for 800 m races are similar to those previously described for 400 m events, despite substantial differences in absolute speed and metabolic demands.[19] This positive pacing strategy has previously been explained as the need to accelerate rapidly in the early stages of the race to achieve at least the fatigue-threshold running speed as quickly as possible. It has been proposed that this fatigue-threshold running speed is the highest speed that can be maintained throughout any entire event according to the body's physiological limitations, such as pulmonary gas exchange, blood acid-base status and blood lactate concentration.[20] Tucker et al.[16] suggested that, in the 800 m event, the speed set by world-class athletes during the early stages of races was even higher than the fatigue-threshold velocity, and therefore the positive pacing strategy observed concurs with the existence of a metabolic limit on the ability to compensate for lost time later in the race.

Filipas et al.[21] analyzed the pacing behavior of 142 800 m SB performances of world-class athletes in meet races and found sex-based differences in pacing. Although the first 200 m split time was always faster than any other 200 m segment, in the men's races the last three 200 m split times were progressively slower, whereas in women's races the remaining 200 m split times did not differ. Consequently, it has been suggested that the relatively slower second 200-m segment for women is caused by the relatively lower performance standard in women's competition.[21] This could mean that female 800 m runners are not required to maintain a very fast initial pace during the second 200-m segment to retain their race position in the same way that men are.[21] However, these pacing strategies are not always followed during major championship races, where the primary goal is to achieve a high finishing position and not necessarily a fast time. It is also possible that the strategic and tactical pacing behaviors displayed in championship races are influenced by the behaviors of the dominant athletes at that time. Sandford et al.[17] has described two different time eras in recent global championships (Olympic Games and IAAF World Championships): 2005–2009 and 2011–2016. In the latter era, and because of the dominance of the front-running David Rudisha, the pacing strategies adopted during the finals were positive, with a faster first lap. However, in the former era, championship races were characterized by negative splits with a faster second lap.[17] Therefore, an athlete's pacing strategy in a race is influenced by the behavior of opponents,[3] whereas a dominant athlete can decide to start quickly and adopt a positive pacing profile. In the case of David Rudisha, who won the 2012 Olympic final in a world record time, it is possible that his strategy was to run fast from the beginning, knowing that it would result in an overall positive pacing profile but would be unsustainable for his rivals, whose strategy was most likely to follow Rudisha for as long as possible. That six of his seven rivals in that race recorded personal best (PB) times is a testament to performances made possible by simply following a dominant front-runner, and unintentionally showed the value of having an excellent pacemaker. Thus, present-era runners might face specific circumstances similar to those described in the pacing strategies used during former 800 m world record perfomances,[16] in which runners overcame the fatigue-threshold speed early during the first lap, thereby achieving faster overall performances, like those achieved during Rudisha's world record performance. However, runners in the former era did not even reach the fatigue-threshold speed during the first lap, and further displayed an inability to make up lost time during the second half.[20]

Few 800 m races follow the pattern set in the men's 2012 Olympic final. However, the positive pacing strategy observed in most world-class 800 m races[14,15,18,19] was also observed during the qualifying heats and semi-finals of the 2017 IAAF World Championships,[22] suggesting that pacing behavior is not primarily influenced by different competitive goals (i.e., qualification for the next round of a championship either directly or as a "fastest loser" (those athletes who ran the fastest times out of all those who did not earn an automatic qualifying spot in a heat or semifinal and qualified for the next round), or attempting to achieve the fastest possible time during a non-championship race). Furthermore, Hanley and Hettinga[23] highlighted the need for runners to optimize their tactical approach during major championships because the differences in the finishing times between qualifiers and non-qualifiers to the next round, or between medalists and non-medalists, are extremely small. Men and women competing in 800 m races at the 2008 Olympic Games and the IAAF World Championships in 2013 and 2017 displayed similar pacing behaviors[22,24] (Fig. 2A and B), as did successful and non-successful runners (i.e., qualifiers vs. non-qualifiers in heats, and medalists vs. non-medalists in finals). These analyses found similar pacing strategies in heats, semi-finals and finals, with the highest speeds achieved over 200 m, followed by deceleration to 300 m, a constant speed to 500 m, another increase in speed to 600 m, and then maintenance or deceleration to the finish, which the authors described as “seahorse-shaped”[25] and showed that a simple description of 800 m championship races as positive pacing (based on analyzing the race in two halves) belies the varied, tactical racing that actually occurs, and which requires different training practices from more evenly paced meet races.

Rather than analyzing only running speeds during championship 800 m races, Casado and Renfree[22] and Renfree et al.[26] studied the relationship between intermediate positioning (at 400 m) in the qualifying rounds and eventual race outcomes. Positions throughout the races remained relatively stable, and the probability of subsequent qualification for the next round was highly related to position at the halfway point in the race. Casado and Renfree[22] also found that the ability to produce a fast final lap relative to a runner’s competitors was the primary determinant of success. Therefore, the ability to qualify for major championship finals is partially determined by the athlete’s ability to adopt a position close to the race leaders from the early stages and to retain the ability to run a fast second half, with the world’s best athletes focused more on a very high finishing position rather than on the time achieved.[23] According to these studies, adopting a high position in the first 200 m by covering this distance more quickly than it is covered during rest of the race is associated with high finishing times and positions in world-class 800 m races.[16,17,22,25]

5. 1500 m and mile

1500 m and mile (1609 m) races are characterized by a high aerobic component (84% ± 1% in the 1500 m event, mean ± SD)[27] and, in contrast to the 800 m event, athletes are not confined at any time to their own lane. Noakes et al.[28] analyzed pacing patterns in 32 world record performances for the mile run and found that 90% of the slowest laps were either the second (34%) or third (56%) of the four laps. Foster et al.[29] subsequently reported that there was a progressive reduction in lap-to-lap variability during these world record performances over time, implying that a more even strategy results in optimization of physiological resources. In these fast non-championship races, the fastest lap was either the first or the last,[28] meaning that fast times are typically achieved using a parabolic U-shaped pacing strategy.[5] This was also the profile displayed during the current men's 1500 m world record performance by Hicham El Guerrouj, although a parabolic J-shaped profile was observed for the current women's 1500 m world record by Genzebe Dibaba in 2015.[29,30] Thiel et al.[24] also observed differences in pacing behavior between 1500 m finalists at the 2008 Beijing Olympic Games and the world records set at the time of those Games. The championship races were characterized by more stochastic fluctuations in pace, meaning that overall there were more microvariations in speed than in the world record performances, which were commonly set during meet races.[24]

During major championship 1500 m races, a parabolic J-shaped pacing profile is typical, where athletes begin at moderate speed on the first lap, slow their speed on the second lap, increase their speed between 700 m and 1300 m, and eventually maintain or decelerate their speed during the final 200 m[22,25] (Fig. 2C and D). This pacing profile means that although overall championship races are generally completed in times slower than the competitors' SBs,[26] to finish in the leading positions athletes must produce far higher absolute running speeds in the final lap.[20,21] Therefore, in addition to developing a high aerobic power,[27] athletes must also develop a high anaerobic capacity[25] to compete effectively in middle-distance events. This capacity is a key performance-related aspect because when covering the last 200 m of a championship race after a long acceleration phase, successful runners are able to maintain speed without slowing down.[20,22] In addition, as was the case in the 800 m event, no sex-based differences in pacing patterns during major championship races were found.[25]

The relationship between intermediate positioning and final race position in 1500 m races at major championships has also been studied. Higher variability in positioning was observed in

1500 m races than in 800 m races,[22] and most athlete accelerations occur on the straights, presumably to avoid running wide on the bends.[22,29] It also has been observed that fastest losers qualified from heats and semi-finals through the adoption of a fast pace relative to their SB time and high intermediate positions in the early stages.[22] Furthermore, being close to the lead or in the leading pack throughout the race was required to win a major championship final, and gold medalists were among the first four runners when the final sprint started during the last lap.[31] Accordingly, it was also found that during qualification races in the IAAF World Championships and Olympic Games, the probability of qualification decreased with intermediate positions after each lap.[22,26] However, further studies are needed to assess intermediate positioning and its influence on performance in 1500 m meet races.

6. 3000 m steeplechase, 5000 m, and 10,000 m

The 3000 m steeplechase and the 5000 m and 10,000 m events are the longest distances run in track races at international championships, and their physiological demands are dominated by aerobic metabolism.[32] 5000 m and 10,000 m world record performances from 2008 onwards were achieved through an even pacing strategy.[24] However, analysis of the pacing patterns displayed during previous 32 5000 m and 34 10,000 m world record performances revealed U-paced profiles where the first and the last 1000 m segments were faster than the even pace adopted during the rest of the race in both events.[16] This behavior provides evidence for the maintenance of a physiological reserve capacity achieved through the actions of a subconscious regulatory mechanism that modifies exercise intensity in an anticipatory manner to prevent catastrophic loss of physiological homeostasis.[33] However, as in 1500 m events, pacing behaviors during major championships differ substantially from those in world record performances.[24,34] For example, Thiel at al. [24] found that pacing profiles during the men's and women's 5000 m and 10,000 m finals at the 2008 Olympic Games had many microvariations that were similar to those observed during the 1500 m events. The objective of this tactic might be related to the absence of pacemakers during this type of race, with the goal of most athletes being the achievement of the highest possible finishing position rather than the fastest possible finishing time. The 5000 m and 10,000 m races present situations where varying pace is more challenging, which allows the very best athletes to separate themselves from rivals.

More recently, the pacing strategies used by 5000 m and 10,000 m finalists in two IAAF World Championships and two Olympic Games and have been analyzed.[34,35] (Fig. 3A–D). Again, the pacing profiles displayed substantially differed from those shown during world record performances and were characterized by a negative pacing strategy in which athletes finishing within the top 8 positions, and especially medalists, started slowly but finished with a very fast endspurt.[16,34] By contrast to 5000 m and 10000 m events, the 3000 m steeplechase finals held at the 2008 and 2016 Olympic Games showed a fast first 228 m (without barriers) followed by a decrease in speed and a subsequent even pace throughout the race until the last endspurt, resulting in a parabolic U-shaped pacing profile[36] (Fig. 3E and F). Therefore, pacing strategies differed between events. In the 5000 m race, sex-based differences were present in that among male medalists, the top 8 and non-top 8 finishers reached the 4000 m distance together, whereas the women who finished outside the top 8 dropped off the leading group after approximately 3000 m.[34,35] In addition, women's 5000 m runners adopted a more even pace (Fig. 3D). The more even paces for women might have occurred because, among other factors, women possess proportionately larger areas of slow twitch (type I) muscle fibers that resist fatigue better.[37] However, in the 10,000 m races, there were no considerable sex-based differences although, as occurred during the 5000 m, the top 16 finishers in the men's race slowed when compared with the lead pack from 8000 m onwards only and, by contrast, the top 16 women separated from the pack from 4000 m onwards.[34,35] Sex-based differences did exist in the 3000 m steeplechase, with women running relatively faster than men in the early stages.[36] In contrast to the 5000 m and 10,000 m races, non-top 8 finalists and non-qualifiers during the women's 3000 m steeplechase heats had a less-even pacing profile than men achieving the same finishing positions.[36] In addition, these less-successful female steeplechasers separated from the front pack relatively earlier than their counterparts in the longer events[36] (Fig. 3B). Pace was more affected by the water jump in women, suggesting that technical efficiency over the barriers should be developed to be able to increase pace in the later stages.[36] Therefore, the particular sex-based differences observed in the 3000 m steeplechase, which differed from those in 5000 m and 10,000 m events, might be related to the fact that the dimensions of the water pit are the same for both sexes, thus influencing performance more negatively in women.[36] Furthermore, the 10,000 m event was run at a more even pace than the 5000 m and 3000 m steeplechase, followed by noticeable acceleration during the last 1000 m.[34–36] These authors stated that the pacing patterns by athletes finishing outside the top 8 positions were different because of a different range of abilities displayed in men's and women's events. Amongst the men, performance times in the 5000 m and 10,000 m events were more similar to each other than amongst the women[34,35] (i.e., the women were more spread out in terms of ability) and, as with the shorter events, this shows that just a few dominant athletes can almost "distort" the pacing patterns observed. As an example, the Ethiopian long-distance runner Almaz Ayana suddenly accelerated after 4000 m in the women's 10,000 m final during the 2017 World Championships, which clearly separated Ayana from her rivals and produced a positive pacing profile (i.e., the first and second 5000 splits were 15:51.38 and 14:24.96, respectively; www.worldathletics.org). A large correlation was found between the best times achieved by athletes in meet events during the 32 months before a major championship and the performance achieved during the championships in the 5000 m and 10,000 m events, suggesting that in long-distance track events recent performances achieved during meet events could be considered an index of future championship performance,[34] despite differences in pacing strategies.

Aragon et al.[31] found that 5000 m race winners were usually within the first five positions at intermediate stages of races, further highlighting the relevance of both being close to the front of the race and drafting in middle- and long-distance running races. Davies[38] found that the energy cost of overcoming air resistance on a calm day was approximately 4% for middle-distance running (at 6 m/s) and 2% for marathon running (at 5 m/s). Pugh[39] showed that 80% of the energy cost in overcoming air resistance could be abolished by drafting 1 m behind another runner, but admitted that such close drafting was difficult in practice (a treadmill was used in his tests). By contrast, Kyle[40] calculated that middle- and long-distance runners reduced energy consumption by only 2%–4% by shielding from the wind. Although the beneficial effects of drafting and running have been experimentally demonstrated in terms of both energetic cost of running[41] and psychophysiological responses,[42] further research is needed to properly understand the interactions among group members during distance running races and their effects on performance.[3] With regard to other tactical decisions, Aragon et al.[31] found that successful athletes typically commenced a final sprint during the last lap on the back straight and, in the case of 5000 m, were within the leading three positions at this distance. These authors also found that in both the 1500 m and 5000 m events, sprints during the last lap were initiated by winners in the inner or central part of lane 1. This observation is similar to that of Jones and Whipp,[15] who also demonstrated a negative impact of covering additional distance on the bend at fast paces during the men's 5000 m final race at the 2000 Olympic Games, which highlights the importance of tactical decision-making in optimizing a runner's physiological resources.

7. Cross country races

Cross country races are unique because the finishing time is irrelevant in that course characteristics vary greatly among competitions.[43] Analyses of 10 (from 2002 to 2013)[43] and 6 (from 2007 to 2013)[44] men's IAAF World Cross Country Championships, all of which were approximately 12 km long, revealed important differences in pacing profiles by participants who were more, or less, successful. Although most athletes were close to the leading pack during the initial stages of the races, they ended up dropping behind the pack and continually decelerated throughout the race (a positive pacing strategy).[43,44] This strategy could also occur because many more runners start the race together than in track competitions, and a "herd"-oriented behavior is thus more frequently selected.[45] Specifically, 61% of the athletes dropped off from the pack (i.e., athletes who were within 1 s of each other) and ran within 105% of the winner's lap time,[43] supporting the recommendation to athletes competing at these championships to adopt more even paces through a more conservative start.[43,44] This positive pacing behavior of less successful runners, characterized by a reduction in muscular rate before the endpoint, could be caused by the afferent feedback from the peripheral physiological systems reporting a risky loss of homeostasis through premature fatigue.[2] Similar to middle- and long-distance track races,[22,25,34,35] eventual gold medalists separated from the other medalists during the last 2 km lap although they did not separate from the other top 15 finishers until the end of the third lap (6 km),[43,44] further suggesting an importance of drafting to conserve energetic resources during middle- and long-distance running races.[39,41,42] Whereas 5000 m and 10,000 m world record performances are characterized by a U-shaped pacing strategy and major championship races show a negative pacing strategy with microvariations in pace, the World Athletics Cross Country Championship races are consistently characterized by a positive pacing strategy. However, a more recent analysis during the 2017 IAAF World Cross Country Championships compared men's and women's pacing strategies for cross country races over the recently adopted equalized distance of 10 km[46] (Fig. 4A and B). In contrast to previous analyses, men displayed a fast endspurt during the last 2 km lap, which might be explained by the shorter distance.[46] Furthermore, both men and women adopted a positive pacing strategy[46] (Fig. 4A and B), and these results differ from those that showed women used more even paces during long-distance track races[34,35] and from other studies that found that men slowed more during 10 km and marathon races.[47,48] This phenomenon might be explained by the fact that, in contrast to other types of races, finishing times are not of importance during cross country races, but finishing positions are (especially because there is also a team competition). Also, because of the varying terrain in cross country races, an athlete's speed is not a reliable reference for indicating that an excessive pace has been adopted.

8. Half marathon and marathon

Research on six World Half Marathon Championships showed that the first 5 km segment was the fastest, whereas the fourth 5 km segment was the slowest but was followed by a faster final 1.1 km[49] (Fig. 4C and D). However, a limitation of analyzing this endspurt was the low resolution of data available. Regardless, the most important contribution of that study was the analysis of the formation, maintenance and breaking up of packs of runners. Athletes who ran in a pack travelling at a suitable speed until at least 10 km slowed less than those who (1) had joined a pack that covered the first 5 km too quickly, (2) dropped behind a pack early in the race, (3) ran most of the distance alone, or (4) moved from one pack to another.[49] Similar findings regarding the influence of initial pace on the formation of packs and further slowing down were reported during 8 IAAF World Marathon Championships.[35,48] Renfree and St Clair Gibson[50] also found that the top 25% of finishers in the women's 2009 World Marathon Championships adopted a more even pace than their rivals, who adopted initial speeds representing a greater proportion of their PB times and progressively slowed. Similarly, the pacing strategy adopted by most competitors in championship marathons (approximately 95% of men and 87% of women) was to run the second half of the marathon slower[35,48] (Fig. 4E and F). In addition, other variables such as course gradient and weather conditions have to be considered when analyzing pacing distribution in elite marathoners. In this regard, it was concluded that when those aspects were assessed in the men's marathon world record performances achieved in 2008 and 2011 with times of 2:03:59 and 2:03:38, respectively, pacing was not optimal and these athletes could have achieved faster performances by adopting the "even" power pacing principle.[51] Regarding the influence of gradient on pacing strategies, it was observed recently that in contrast to other World Marathon Championships, winning performances in the New York Marathon had a negative pacing pattern because of its uphill profile during the beginning of the race and its downhill profile during the final stages.[52] In contrast, winning performances in the Berlin Marathon were faster and displayed a more even pace because of its almost flat course profile.[52] Additionally, a recent study[53] found that the pacing strategy used to achieve world record performances in the men's marathon differed depending on whether the world records were set between 1967 and 1988 (described as "classic") or between 1988 and 2018 ("contemporary"). Classic records displayed a positive pacing profile, where a fast start was followed by a substantial decrease in pace from 25 km onwards until the very end of the race, when an endspurt occurred. Contemporary records were characterized by a negative pacing pattern, in which the second half of the marathon was covered faster.[53] One of the likely cause for this difference was the absence of pacemakers during most of the classic world record performances in contrast to contemporary world record performances. Consequently, a positive pacing strategy would allow athletes setting classic world records to avoid the psychological load of maintaining a constant specific pace during the first stages and allow them to maintain it during the later stages. In addition, the positive strategy used to achieve classic world records could be attributed to the particular glycogen depletion (which leads to hypoglycaemia and hyperthermia) observed in this long event.[54] However, the negative pacing profile observed in contemporaneous records that have predominantly been achieved by East African runners might also be explained by some of their training characteristics, e.g., they usually cover longer distances either at or close to specific marathon pace than European runners.[55] Consequently, the greater accumulation of training volume at this speed range has been associated with better performances in world-class long-distance runners.[56] Therefore, these runners might experience stimuli during training that is similar to what is experienced during the race, which in turn may provoke certain adaptations that outweigh the particular impairing effects of glycogen depletion on performance. As noted above, Davies[38] observed that the energy cost of overcoming air resistance in calm weather conditions was approximately 2% for marathon running (at 5 m/s); more recently, the effect of different cooperative drafting scenarios on marathon performance has been modeled and, given that elite distance running performance has evolved during the last three decades, the effect of drafting in these new faster races has become more relevant.[57] Furthermore, research comparing the pacing strategies in men's and women's marathon world record performances since 1998 reveals that women adopted a more even pace (when paced by other women) whereas men displayed a more negative pace.[58,59] As with records set over shorter distances, this highlights that running at an even pace is most likely to result in the fastest finishing times and that such a pacing strategy is facilitated by favorable weather, a well-prepared pack of pacemakers and flat courses. Table 1 indicates the different observational studies used to conduct the current review.

9. **Further research**

The observational research described here analyzed the pacing behavior of elite athletes during world-class races. However, this approach is typically based on the analysis of existing performance data available in open-access datasets presenting results of either major championships or meet races. Therefore, although they provide highly ecologically valid performance data, the studies reviewed here provide little information regarding the underpinning mechanisms that explain the behaviors shown. For example, there are no data regarding the specific weighting given to the importance of internal physiological or external environmental information on informing pacing decisions in elite runners. Further research should be conducted in which interventions are used to alter either physiological or psychological states before participation in exercise protocols performed in a controlled simulated competitive environment. Alternatively, to assess the influence of drafting on performance and physiological and psychological determinants, researchers should attempt to control participants' pre-exercise states before the completion of exercise tasks. These proposed studies should involve competition against either avatars or other participants who have been instructed to behave in a specified manner. Additionally, to identify the particular contribution of different variables in elite middle- and long-distance running races, mathematical models should be generated. For example, Trenchard, Renfree, and Peters[60] modelled the influence of competitors on the collective behavior of competitors in a 10,000 m elite race and concluded that behaviors cannot be fully explained through drafting effects and that psychological processes are therefore involved in the mechanisms underpinning collective behavior. A potential advantage of this method is that it allows greater isolation and control of individual variables, as well as the running of large numbers of simulations. Although these simulations have been unable to recreate observed collective behavior and pacing in running events to date, further developments of this model could eventually allow the creation of realistic simulations. Furthermore, data explaining psychological factors such as affective valence (how pleasant or unpleasant a specific exercise is perceived to be) could be collected from elite athletes and used to explain their pacing behavior. For example, unexpected intermediate positions displayed by elite runners during a race might lower their affective valence and thereby influence negatively their final performance.[42] However, the specific influence on performance of these and other psychological variables may not be either explained or quantified by a simulation. Finally, practical interventions are needed to make a meaningful positive impact on the discipline. As described previously, common underperforming pacing behaviors during elite long-distance running races are characterized by early paces that are too fast. Therefore, to develop more optimal and successful pacing behaviors, further interventions should try to enable athletes to deliberately establish adequate and non-excessive early paces that are not influenced by poor decisions made by other competitors.

10. Conclusions and practical applications

Pacing strategies adopted by world-class and elite athletes differ among individual sports, such as cycling, swimming and speed skating. Therefore, the study of sport-specific pacing profiles is necessary. In this review, we provide a comprehensive analysis of pacing in running events, which is summarized in Table 1, 100 m and 200 m races run by elite runners are characterized by an all-out pacing strategy, in which maximal speed is achieved in the early stages of the 200 m event and at approximately the halfway distance in the 100 m event, with a subsequent decrease in speed in the later stages. During world-class 400 m races, a positive pacing pattern is adopted, in which a high speed is achieved during the early stages of the race, and athletes subsequently slow with distance covered. 800 m pacing profiles indicate that a positive profile is similarly used, with a faster first lap that results in a unique seahorse-shaped pacing profile, although negative splits are sometimes produced during tactical races at major championships. Additionally, success in the 800 m event is related to the runner's ability to get close to the race leaders from the beginning and produce a fast second lap. Performances in races distances of 1 mile and 1500 m display a parabolic U-shaped pacing strategy, with 1500 m athletes adopting a parabolic J-shaped profile during major championships. Therefore, 1500 m runners should train to be physiologically prepared to cover the last lap of a major championship event much faster than the mean speed adopted in achieving the championship qualifying time during a meet race. A parabolic U-shaped profile characterizes the 3000 m steeplechase and the 5000 m and 10,000 m races, although a high number of microvariations of pace are found during championship races for these distances. Therefore, to succeed during major championships (e.g., during the final stages), 5000 m and 10,000 m runners should be prepared to compete and run at a relatively high speed whilst repeatedly varying the pace. 3000 m steeplechasers should develop their technical abilities that will allow them to overcome barriers and enable them to increase their pace in the later stages of the race. Furthermore, to win a medal or achieve a qualifying position during 1500 m and 5000 m major championship races, runners should stay with the lead runners during the last lap. In addition, middle- and long- distance track runners might benefit from drafting opportunities. 800 m runners in major championship events should avoid running wide on the bends throughout the whole race; and runners in 1500 m, 5000 m, and 10,000 m races should try to run wide only during the decisive stages of the race when the speed is high. During major championships, a positive pacing strategy is typically displayed by cross country runners, parabolic U-shaped pacing is displayed by half marathoners and positive pacing is displayed by marathoners. It is recommended that athletes whose goals do not extend to winning a medal or finishing in a top position maintain a realistic and conservative pace during the initial stages of long-distance races and stay within a pack of runners for most of the race. Coaches of elite athletes should very carefully note the difference in pacing profiles adopted in meet races (where a pacemaker is often used) and the pacing used in championship racing. Fast times achieved in meet races with one or multiple pacemakers are not necessarily replicated in winner-takes-all championship races, where the pace can vary considerably.

Authors' contributions

AC devised and drafted the study and critically revised the intellectual content; BH, PJR, and AR revised the study critically for intellectual content and approved the final version for publication. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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Table 1 Summary of observational studies that have reported pacing strategies conducted by world-class and elite athletes at different events during international athletics running races.

Study	Distance	Competition	Sex	Pacing strategy
Ferro et al. (2001)[7a]	100 m, 200 m, 400 m	WC	Men and women	All out, all out, positive
Bissas et al. (2018)[8,9]	100 m	WC	Men and women	All out
Pollitt et al. (2018)[10–13a]	200 m and 400 m	WC	Men and women	All out, positive
Tucker et al. (2006)[16]	800 m	WR	Men	Positive and seahorse
Sandford et al. (2018)[17]	800 m	WC, OG (F)	Men	Negative and positive
Filipas et al. (2018)[21]	800 m	SB	Men and women	Positive
Thiel et al. (2012)[24b]	800 m	WR, OG	Men and women	Positive and seahorse
De Koning et al. (2011)[18]	800 m	WR	Men	Positive
Casado et al. (2018)[22]	800 m	WC (Q)	Men and women	Positive
Hanley et al. (2019)[25]	800 m	OG, WC	Men and women	Sea horse
Hettinga et al. (2019)[35]	800 m	OG, WC	Men and women	Sea horse
Casado et al. (2018)[22]	1500 m	WC (Q)	Men and women	Reverse J-shaped
Hanley et al. (2019)[25]	1500 m	OG, WC	Men and women	J-shaped
Hettinga et al. (2019)[35]	1500 m	OG, WC	Men and women	J-shaped
Mytton et al. (2015)[61]	1500 m	OG, WC, EC (F)	Men	J-shaped
Aragón et al. (2016)[31]	1500 m	OG, WC, EC (F)	Men	Negative
Thiel et al. (2012)[24b]	1500 m	WR, WC	Men and women	Reverse J-shaped and J-shaped
Noakes et al. (2009)[28]	Mile (1609 m)	WR	Men	U-shaped
Hanley et al. (2020)[36]	3000 m steeplechase	OG	Men and women	U-shaped
Tucker et al. (2006)[16]	5000 m	WR	Men	Even with endspurt
Filipas et al. (2018)[34]	5000 m	OG, WC (F)	Men and women	Negative

Hettinga et al. (2019)[35]	5000 m	OG, WC (F)	Men and women	Negative
Aragón et al. (2016)[31]	5000 m	OG, WC, EC (F)	Men	Negative
Thiel et al. (2012)[24b]	5000 m	WR, WC	Men and women	Even and negative.
Tucker et al. (2006)[16]	10,000 m	WR	Men	Even with endspurt
Filipas et al. (2018)[34]	10,000 m	OG, WC (F)	Men and women	Even with endspurt
Hettinga et al. (2019)[35]	10,000 m	OG, WC (F)	Men and women	Even with endspurt
Thiel et al. (2012)[24b]	10,000 m	WR, WC	Men and women	Even and negative
Hanley (2014)[43]	Cross country	WC	Men	Positive
Esteve-Lanao et al. (2014)[44]	Cross country	WC	Men	Positive
Hanley (2018)[46]	Cross country	WC	Men and women	U-shaped
Hanley (2015)[49]	Half marathon	WC	Men and women	Even with endspurt
Hanley (2016)[48]	Marathon	OG, WC	Men and women	Positive
Hettinga et al. (2019)[35]	Marathon	OG, WC	Men and women	Positive
Renfree et al. (2013)[50]	Marathon	WC	Women	Positive
Angus (2014)[51]	Marathon	WR	Men	U-shaped and varied
Díaz et al. (2019)[52]	Marathon	World Majors	Men	Different among courses
Díaz et al. (2018)[53]	Marathon	WR	Men	Positive and negative
Díaz et al. (2019)[58]	Marathon	WR	Men and women	Negative and even
Billat et al. (2020)[59]	Marathon	WR	Men and women	Negative and even

[a] Pacing strategies are indicated for 100 m, 200 m, and 400 m performances in the order listed.

[b] Pacing strategies are indicated for world record performances and for Olympic Games performances in the order listed.

Abbreviations: EC = European Championships performances; F = only final race; OG = Olympic Games performances; Q = only qualification races; WC = World Championships performances; WR = world record performances.

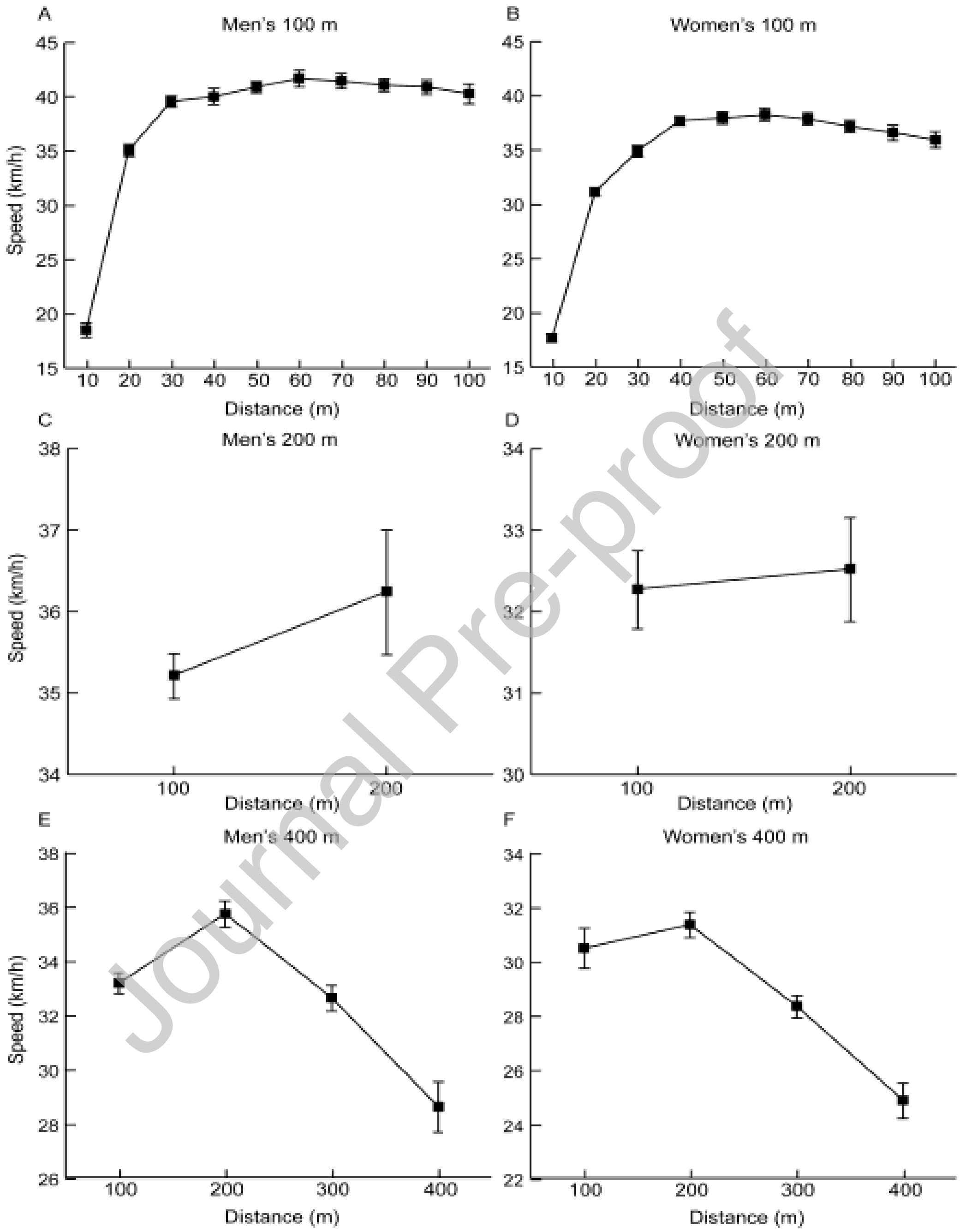

Fig. 1. The 10 m segment speeds for the men's and women's 100 m finals (A and B) and the 100 m segment speeds for the men's and women's 200 and 400 m finals (C–F) at the 2017 IAAF World Championships. Data were obtained from the open-access World Athletics website (worldathletics.org). Data were presented as mean ± SD.

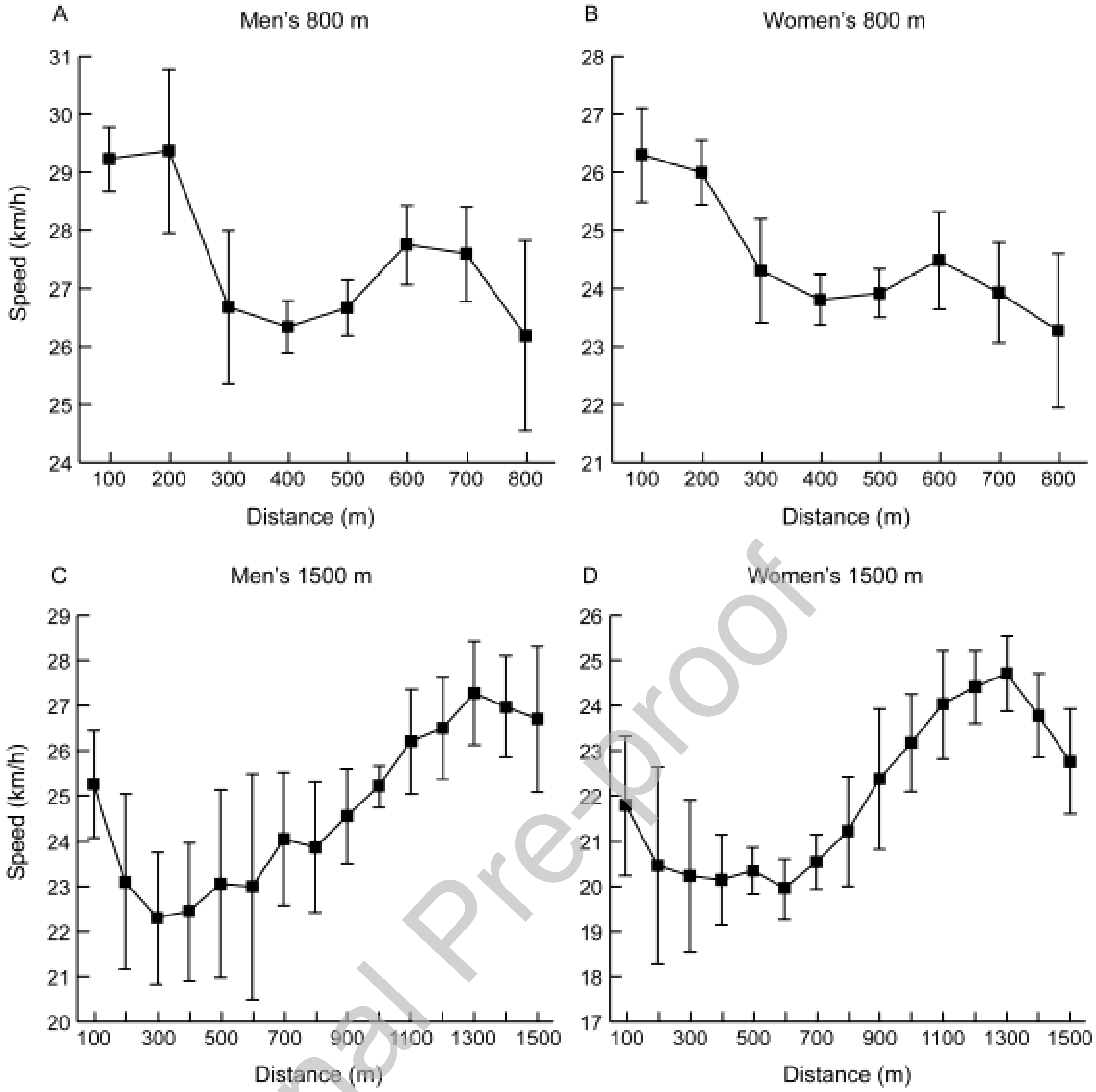

Fig. 2. The 100 m segment speeds for the men's and women's 800 m (A and B) and 1500 m (C and D) finals at the 2008 Olympic Games and 2013 and 2017 IAAF World Championships; data for the 1500 m obtained from the 2016 Olympic Games are also included. Data were obtained from the open-access World Athletics website (worldathletics.org). Data were presented as mean ± SD.

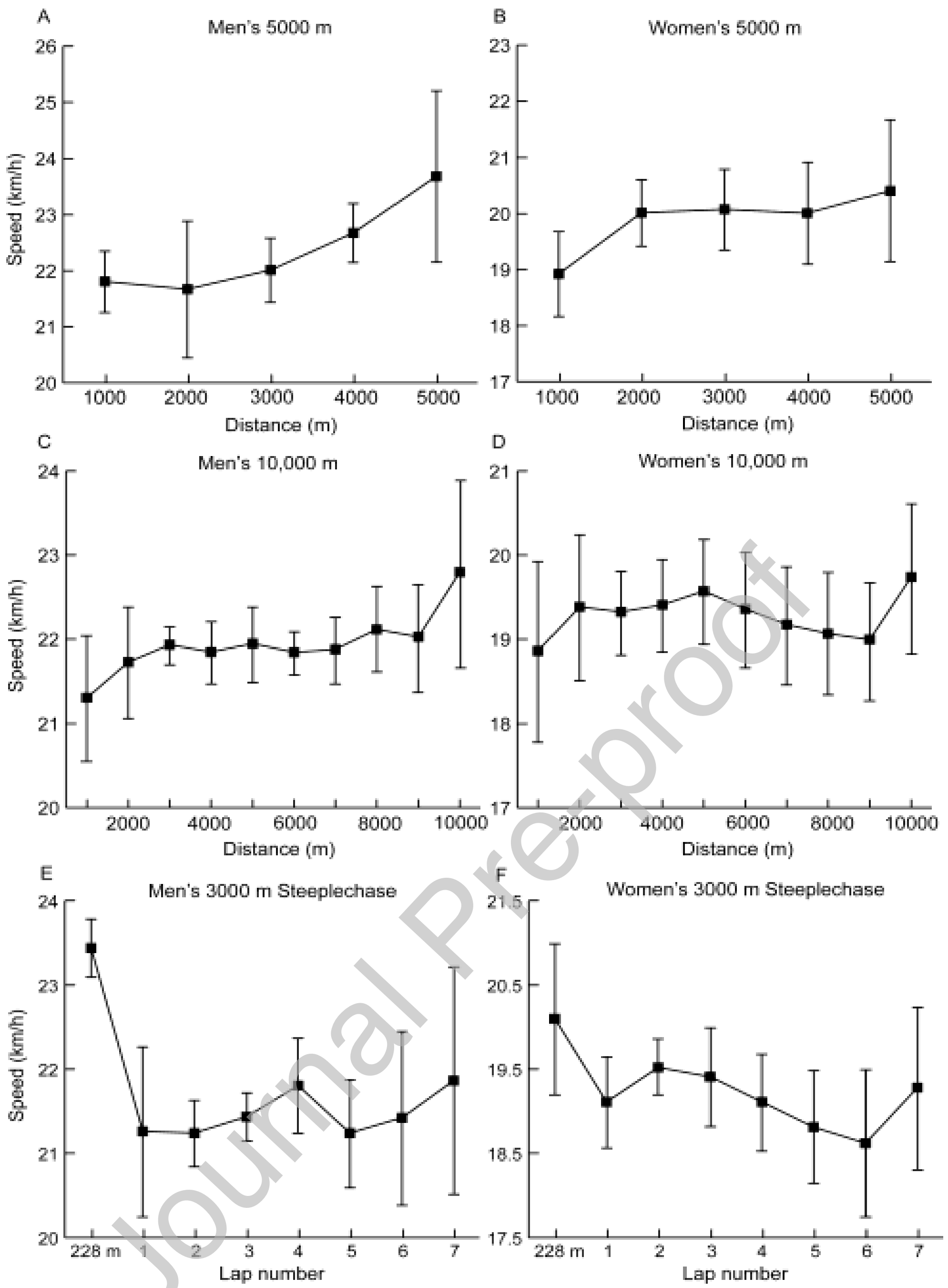

Fig. 3. The 1000 m segment speeds for the men's and women's 5000 m and 10,000 m finals at the 2008 and 2016 Olympic Games and 2013 and 2017 IAAF World Championships (A–D) and the first 287 m segment speeds and speeds for the remaining 7 laps for the men's and women's 3000 m steeplechase finals at the 2008 and 2016 Olympic Games (E and F). Data were obtained from the open-access World Athletics website (worldathletics.org). Data were presented as mean ± SD.

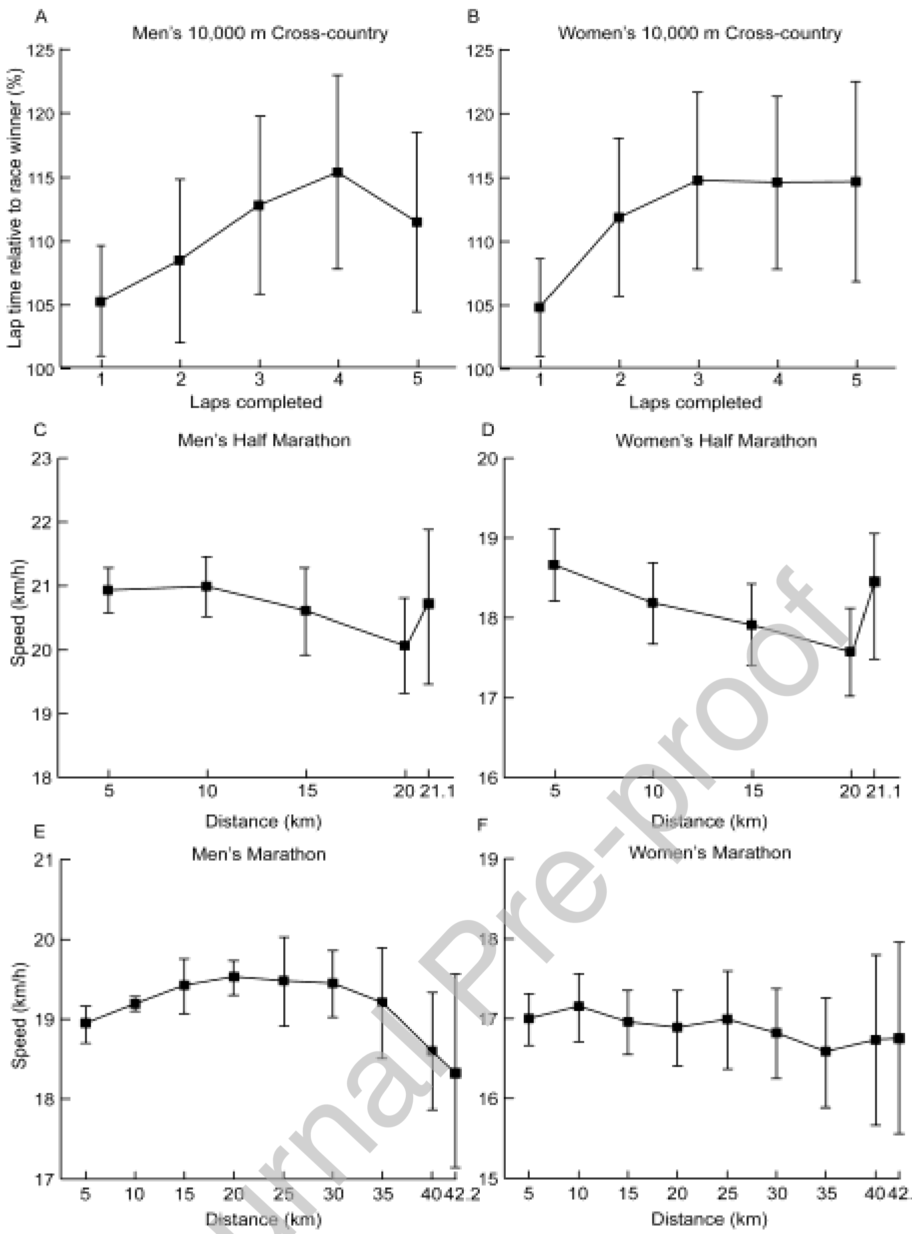

Fig. 4. The 2 km segment speeds for the men's and women's 2017 IAAF World Cross Country Championships (A and B), the 5 km segment speeds and final 1.1 km segment speeds for the men's and women's half-marathon races at six IAAF World Championships from 2007 to 2014 (C and D), and the 5 km segment speeds and final 2.2 km segment speeds for the men's and women's marathon races at the 2016 Olympic Games and 2013 and 2017 IAAF World Championships (E and F). Data were obtained from the open-access World Athletics website (worldathletics.org). Data were presented as mean ± SD.

Graphical abstract